US008267056B2

(12) United States Patent
Dean

(10) Patent No.: US 8,267,056 B2

(45) Date of Patent: Sep. 18, 2012

(54) SPLIT-CYCLE INTERNAL COMBUSTION ENGINE

(75) Inventor: **Charles Dean**, Royal Oak, MI (US)

(73) Assignee: **GM Global Technology Operations LLC**, Detroit, MI (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 379 days.

(21) Appl. No.: **12/724,461**

(22) Filed: **Mar. 16, 2010**

(65) **Prior Publication Data**

US 2011/0226224 A1 Sep. 22, 2011

(51) **Int. Cl.**
F02B 33/00 (2006.01)

(52) **U.S. Cl.** .... **123/68**; 123/70 R; 60/620

(58) **Field of Classification Search** .... 123/68, 123/70 R; 60/39.6, 517, 597, 620
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2,110,248 A * 3/1938 Wagner 123/52.3

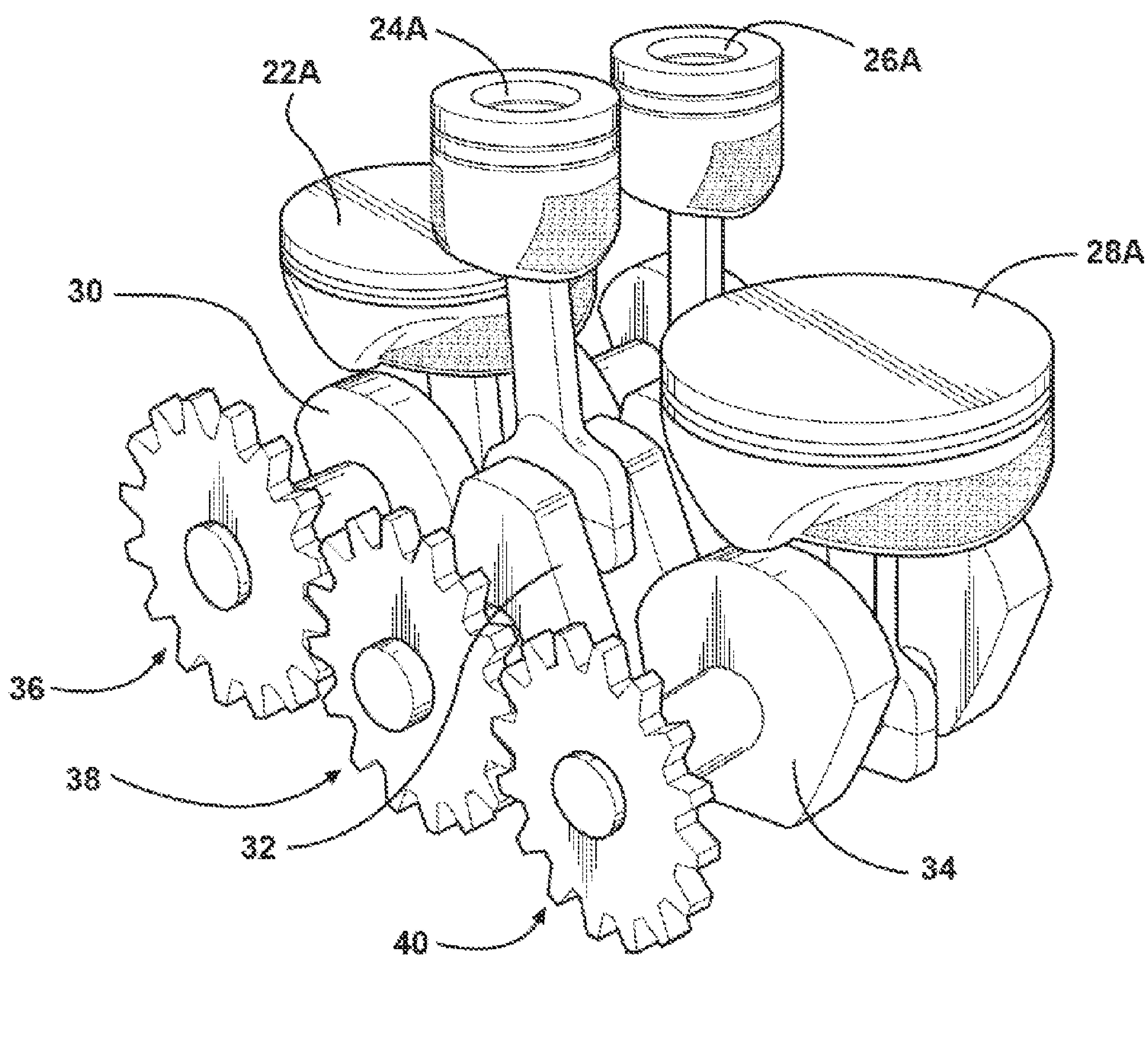
* cited by examiner

Primary Examiner — Noah Kamen
(74) *Attorney, Agent, or Firm* — Quinn Law Group, PLLC

(57) **ABSTRACT**

A split-cycle internal combustion engine is disclosed. The engine includes a cylinder block, and a plurality of cooperating power pistons and cylinders mounted in the cylinder block. The power pistons are configured to be energized by forces of combustion. The engine also includes a compressor piston and cylinder configured to compress a volume of air and transfer the compressed air to the power pistons, and an expander piston and cylinder configured to receive exhaust gases from the power pistons. The engine additionally includes a first crankshaft operatively connected to and rotatably driven by the power pistons, a second crankshaft operatively connected to the compressor piston and configured to rotatably drive the compressor piston, and a third crankshaft operatively connected to the expander piston and configured to be rotatably driven by the expander piston. The first, second, and third crankshafts are operatively connected to each other for coordinated rotation.

20 Claims, 2 Drawing Sheets



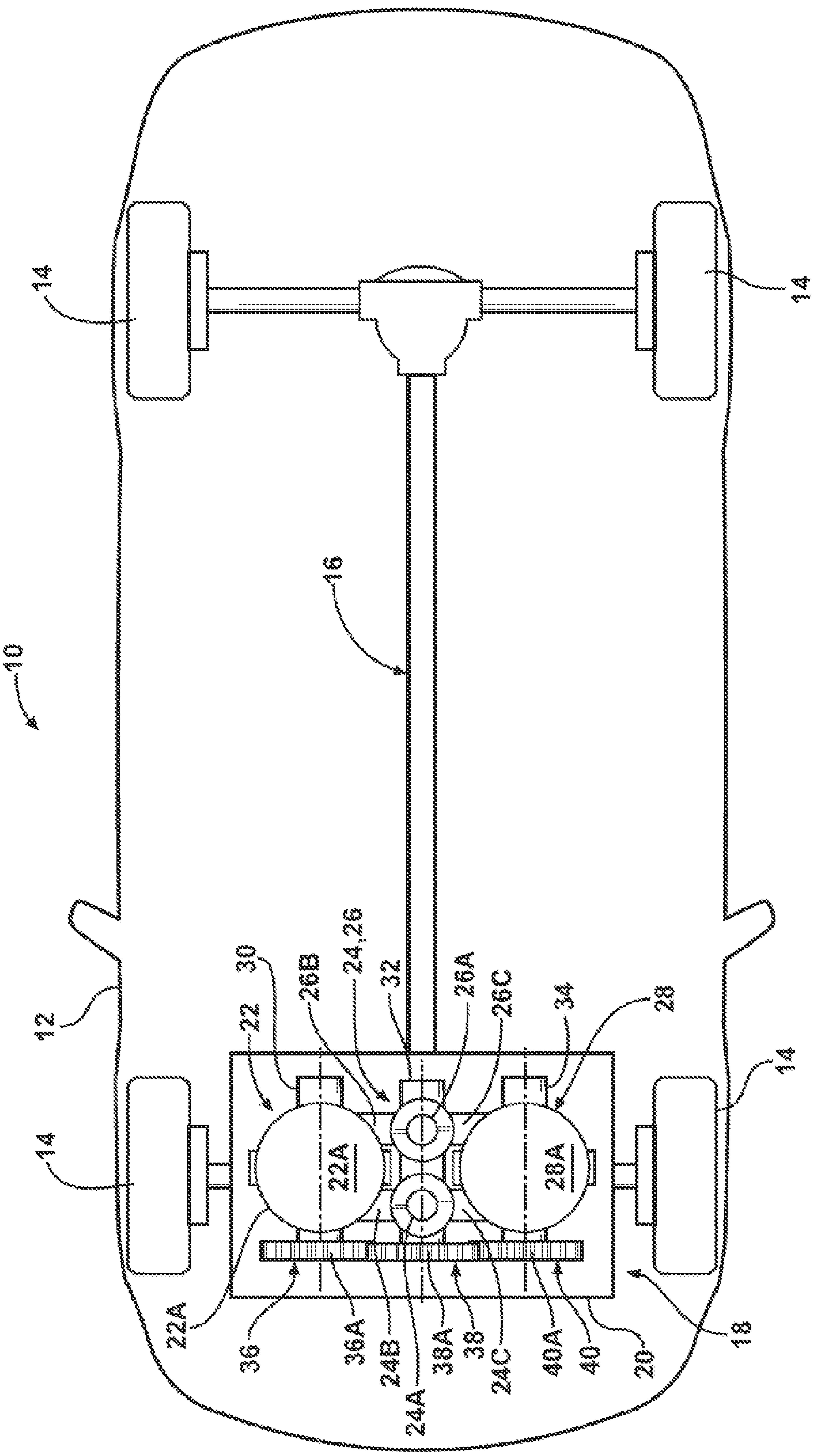

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FIG. 1

FIG. 2

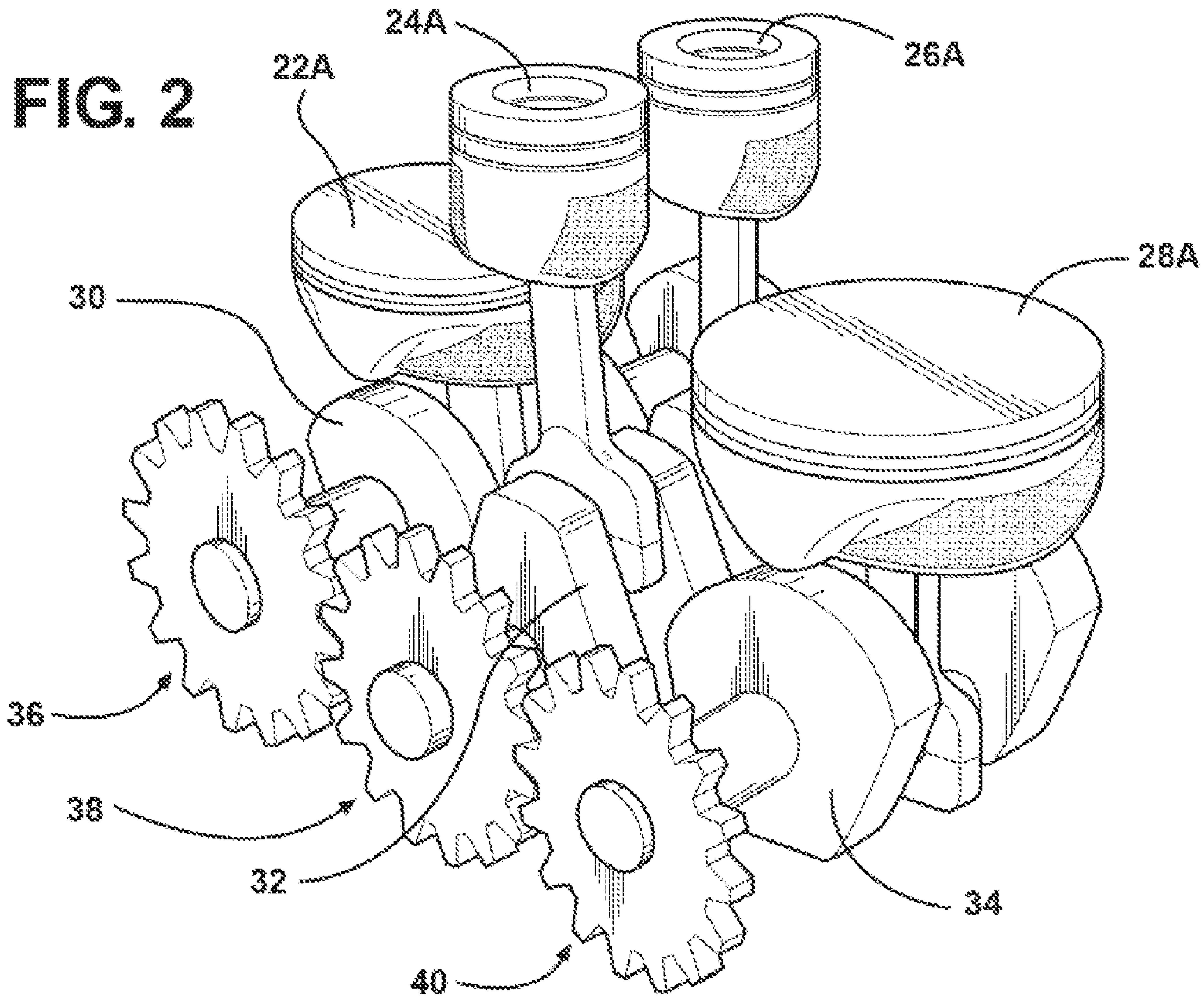
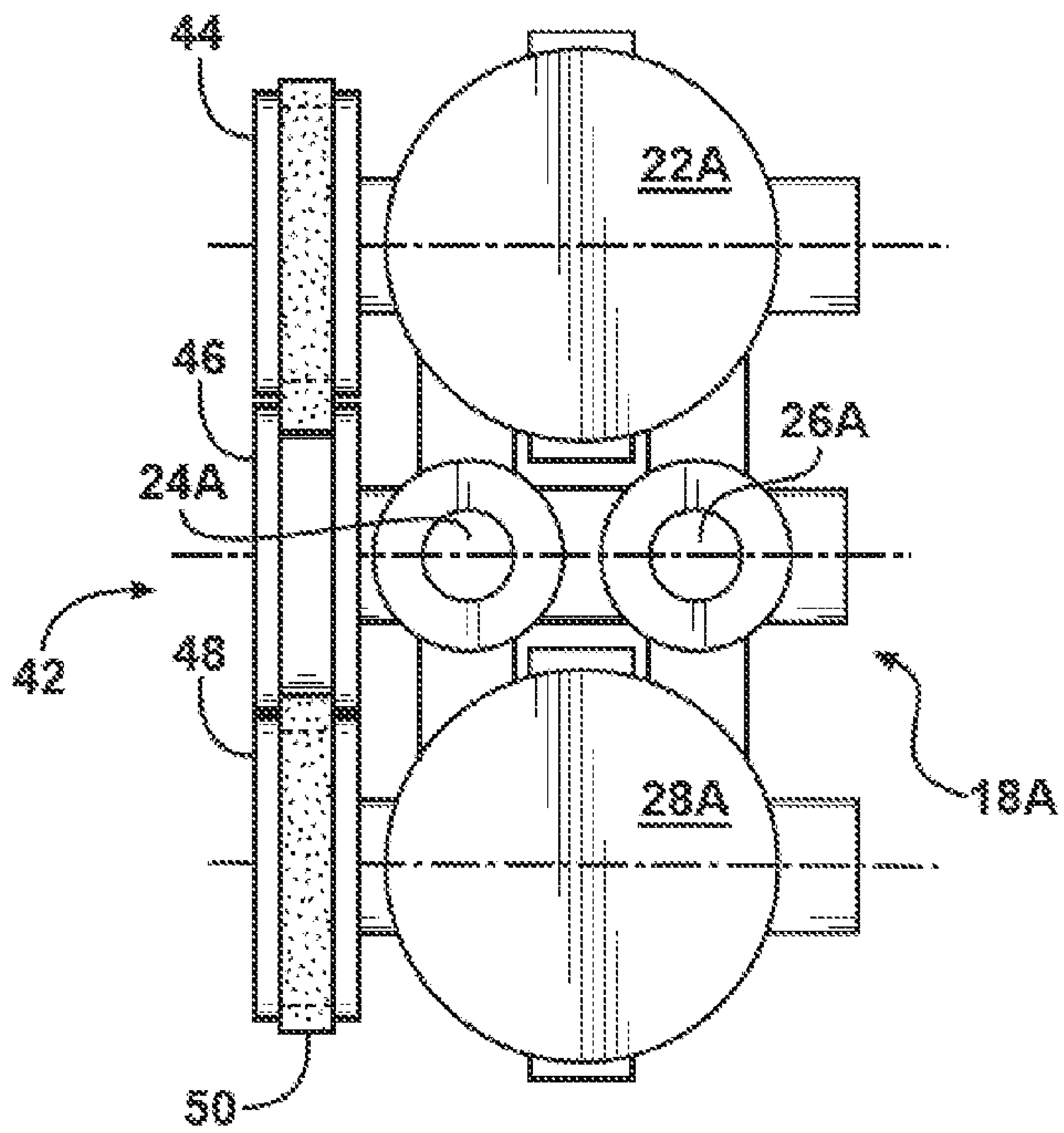


FIG. 3



SPLIT-CYCLE INTERNAL COMBUSTION ENGINE

TECHNICAL FIELD

The invention relates to a split-cycle internal combustion engine and use thereof.

BACKGROUND OF THE INVENTION

In a conventional Otto cycle internal combustion engine, each cylinder performs four strokes per cycle—intake, compression, power, and exhaust. As a result, two revolutions of the engine's crankshaft are required for each power stroke.

By contrast, a split-cycle engine divides these four strokes between at least two paired cylinders—one for intake/compression and another for power/exhaust. In some split-cycle engine configurations compressed air is transferred from the compression cylinder to the power cylinder through a transfer or crossover passage. Fuel is subsequently injected and fired in the power cylinder to produce the power stroke.

Additionally, in some split-cycle engines, an expander cylinder is also provided to take advantage of the energy contained in post-combustion exhaust gases to create additional mechanical work by allowing further gas expansion. In such a case, after the power stroke, exhaust gases are transferred from the power cylinder to the piston expander via an exhaust port or passage, thereby displacing the expander cylinder.

SUMMARY OF THE INVENTION

A split-cycle internal combustion engine is disclosed. The engine includes a cylinder block, and a plurality of cooperating power pistons and cylinders mounted in the cylinder block. The power pistons are configured to be energized by forces of combustion. The engine also includes a compressor piston and cylinder mounted in the cylinder block and configured to compress a volume of air and transfer the compressed air to the power pistons. The engine additionally includes an expander piston and cylinder mounted in the cylinder block and configured to receive products of combustion, i.e., exhaust gases, from the power pistons. Furthermore, the engine includes first, second, and third crankshafts that are operatively connected for coordinated rotation. The first crankshaft is operatively connected to, and is rotatably driven by the power pistons. The second crankshaft is operatively connected to, and is configured to rotatably drive the compressor piston. The third crankshaft is operatively connected to, and is configured to be rotatably driven by the expander piston.

The first, second, and third crankshafts may be disposed alongside and parallel relative to each other. The engine may include an intake port configured to transfer the compressed air from the compressor piston to each of the cooperating power pistons, and an exhaust port configured to transfer exhaust gases from each of the cooperating power pistons to the expander piston. The intake and exhaust ports may be arranged such that the compressor piston is positioned on one side of the plurality of cooperating power pistons, and the expander piston is positioned on the opposite side of the plurality of cooperating power pistons.

The engine may additionally include first, second, and third interconnected gears, wherein the first gear is connected to the first crankshaft, the second gear is connected to the second crankshaft, and the third gear is connected to the third crankshaft. The first, second, and third gears may be interconnected via at least one chain. The first, second, and third gears may be intermeshed, and the first gear may have a handed helix, while the second and third gears have an oppositely handed helix as compared to the handed helix of the first gear.

The engine may also include first, second, and third pulleys, wherein the first pulley is connected to the first crankshaft, the second pulley is connected to the second crankshaft, and the third pulley is connected to the third crankshaft. In such a configuration, the first, second and third pulleys may be operatively connected via at least one belt.

The first, second, and third crankshafts may be operatively connected for synchronous rotation. The second and third crankshafts may additionally be configured as balance shafts for smoothing-out operation of the engine.

A vehicle employing the above described split-cycle internal combustion engine is also disclosed.

The above features and advantages and other features and advantages of the present invention are readily apparent from the following detailed description of the best modes for carrying out the invention when taken in connection with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic illustration of a vehicle employing for propulsion a split-cycle internal combustion engine with three crankshafts;

FIG. **2** is a close-up perspective partial view of the split-cycle internal combustion engine employing intermeshed gears to connect the three crankshafts; and

FIG. **3** is a schematic top partial view of the split-cycle internal combustion engine employing a belt-drive to connect the three crankshafts.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to the drawings, wherein like reference numbers refer to like components, FIG. **1** shows a vehicle **10** having a body **12**, and a plurality of wheels **14**. Vehicle **10** employs a driveline **16** for transferring drive torque to wheels **14** from a split-cycle internal combustion engine **18**. Not specifically shown, but as understood by those skilled in the art, driveline **16** may include a transmission, a driveshaft, and one or more differentials to transfer torque developed by split-cycle internal combustion engine **18** for powering vehicle **10**.

Split-cycle engine **18** may also be employed in a hybrid vehicle application, as understood by those skilled in the art. In such an application, split-cycle engine **18** may be utilized in the capacity of a generator to charge an on-board vehicle energy-storage device, such as a battery pack, at high levels of efficiency and output. Additionally, split-cycle engine **18** may be used for stationary power production, i.e., a stationary generator application.

In general, and as understood by those skilled in the art, a split-cycle internal combustion engine offers improved efficiency over a conventional spark ignition (SI) or a compression ignition (CI) internal combustion engine. As shown, split-cycle engine **18** includes a cylinder block **20**. The cylinder block **20** houses a compressor cylinder **22** and a pair of power cylinders **24** and **26**. Engine **18** additionally includes an expander cylinder **28**. Expander cylinder **28** is configured to create additional mechanical work by utilizing the energy contained in post-combustion exhaust gases. Consequently, the split-cycle engine **18** is a dual-compression, dual-expansion engine, which employs separate compressor cylinder **22** and separate expander cylinder **28** to augment compression and expansion functions, respectively, of power cylinders' **24** and **26**.

A compressor piston **22**A is mounted inside the compressor cylinder **22** and is adapted for reciprocating motion therein; a pair of power pistons **24**A and **26**A are individually mounted inside each of the power cylinders **24** and **26**, and are adapted for reciprocating motion therein; and an expander piston **28**A is mounted inside the expander cylinder **28** and is adapted for reciprocating motion therein. Compressor cylinder **22** is configured to draw a volume of ambient air in on a down stroke of the piston **22**A, compress the volume of air and transfer the compressed air to power cylinders **24** and **26** on an up stroke of the subject piston. Compressor cylinder **22** transfers compressed air to power cylinders **24** and **26** via intake transfer ports **24**B and **26**B, respectively. Intake transfer ports **24**B and **26**B are typically part of either an intake manifold or a cylinder head, neither of which is shown, but each are known by those skilled in the art. Fuel is introduced periodically into each of the power cylinders **24** and **26** via a fuel delivery and injection system (not shown) along with, or shortly after the compressed air is delivered to each respective cylinder. As understood by those skilled in the art, fuel and air combine to produce an air-fuel mixture for subsequent firing and combustion inside cylinders **24** and **26**. The power pistons **24**A and **26**A are prompted into sustained reciprocating motion by successive firing of the fuel-air mixture inside the respective cylinders.

Engine **18** additionally employs three separate crankshafts **30**, **32**, and **34**, disposed alongside and parallel relative to each other. Crankshaft **30** is a compressor cylinder crankshaft operatively connected to and configured to rotatably drive piston **22**A; crankshaft **32** is a power cylinder crankshaft operatively connected to and rotatably driven by pistons **24**A and **26**A; and crankshaft **34** is an expander cylinder crankshaft operatively connected to and rotatably driven by a piston **28**A. The three crankshafts **30**, **32**, and **34** are operatively connected to each other for coordinated rotation. Crankshafts **30**, **32**, and **34** may also be connected for synchronous rotation. A split-cycle engine having more than two power cylinders is also envisioned. Depending on the actual number of power cylinders employed, respective compressor, power, and expander crankshafts may also be connected such that all three crankshafts rotate either at the same speed or at a predetermined speed ratio, as understood by those skilled in the art.

An initial downward stroke of each respective piston **24**A, **26**A after the firing of the air-fuel mixture inside respective cylinders **24**, **26** generates power to rotate crankshaft **32**. Consequently, each successive firing inside the cylinders **24**, **26** maintains rotation of the crankshaft **32**, and transfers rotational motion to crankshafts **30** and **34** via intermeshed gears **36**, **38**, and **40**. After each firing of each power cylinder **24**, **26**, the respective power cylinder on its upstroke expels the post-combustion exhaust gases, and transfers such gasses to expander cylinder **28** via exhaust transfer ports **24**C and **26**C. The expander piston **28**A is in turn displaced or driven by the expansion of the exhaust gases received from power cylinder **24**, **26**. Hence, the energy contained in the transferred exhaust gasses in the form of heat and pressure is thereby used to create additional mechanical work by displacing expander piston **28**A and rotating crankshaft **34**.

As shown in FIGS. **1** and **2**, the coordinated rotation of three crankshafts **30**, **32**, and **34** is achieved via three intermeshed gears, each connected to one of the subject crankshafts. Gear **36** is connected to crankshaft **30**; gear **38** is connected to crankshaft **32**; and gear **40** is connected to crankshaft **34**. Gears **36** and **40** have teeth **36**A and **40**A, respectively. Teeth **36**A and **40**A are characterized by a similarly handed helix. Gear **38** has teeth **38**A that are characterized by a helix that is opposite to that of the gears **36** and **40**, thus permitting the three gears **36**, **38**, **40** to mesh, and provide coordinated rotation of crankshafts **30**, **32**, **34**. A helix is employed in meshed gears **36**, **38**, **40** to allow for quieter operation of engine **18**, through continuous contact between gears and reduction of gear lash, as understood in the art.

Rotational direction of gears **36**, **38**, **40** may be modified with an idler gear (not shown), if needed, such as for the purposes of balancing engine **18**, as understood by those skilled in the art. Coordinated rotation of crankshafts **30**, **32**, **34** may also be achieved by non-intermeshed, non-contacting gears, with the distance between the gears spanned by a chain drive (not shown, but as understood by those skilled in the art). Such a chain drive may include a tensioner to keep the chain drive taut during operation of engine **18**.

FIG. **3** depicts a split-cycle engine **18**A, which is identical to engine **18** shown in FIGS. **1** and **2** in all regards other than having a belt-drive **42**, with each identical element numbered accordingly. As shown in FIG. **3**, coordinated rotation of crankshafts **30**, **32**, **34** may also be achieved by a belt-drive **42**. Belt-drive **42** includes a pulley **44** connected to crankshaft **30**, pulley **46** connected to crankshaft **32**, and pulley **48** connected to crankshaft **34**. A belt **50** spans the distance between the pulleys **44**, **46**, and **48**, to thereby operatively interconnect crankshafts **30**, **32**, and **34**. Belt-drive **42** may include a tensioner (not shown) to keep the belt **50** taut during operation of engine **18**A. While only a single belt **50** is shown, belt-drive **42** may include a plurality of belts as required.

As shown in FIGS. **1-3**, in engines **18** and **18**A piston compressor **22** and piston expander **28** are positioned on opposite sides of, and in close proximity to power cylinders **24** and **26**. Such positioning of piston compressor **22** and piston expander **28** permits the shortest length of intake transfer ports **24**B and **26**B and exhaust transfer ports **24**C and **26**C. The minimized length of exhaust transfer ports **24**C and **26**C is especially beneficial, in order to reduce heat loss and thereby transfer a higher percentage of the exhaust gas energy to cylinder expander **28**. Such configuration facilitates reduction of the length of engines **18** and **18**A. Furthermore, compressor and expander cylinder crankshafts (such as **30** and **34**, respectively) may be additionally configured as specifically weighted balance shafts to offset vibrations in engine designs that are not inherently balanced, such as employing two or four power cylinders. Providing such a counterbalance to the motion of reciprocating cylinders is an effective method to smooth-out operation of engines **18** and **18**A, as understood by those skilled in the art.

While the best modes for carrying out the invention have been described in detail, those familiar with the art to which this invention relates will recognize various alternative designs and embodiments for practicing the invention within the scope of the appended claims.

The invention claimed is:

1. A split-cycle internal combustion engine comprising:

a cylinder block;

a plurality of cooperating power pistons and cylinders mounted in the cylinder block, the power pistons configured to be energized by forces of combustion;

a compressor piston and cylinder mounted in the cylinder block and configured to compress a volume of air and transfer the compressed air to the power pistons;

an expander piston and cylinder mounted in the cylinder block and configured to receive exhaust gases from the power pistons;

a first crankshaft operatively connected to and rotatably driven by the power pistons;

a second crankshaft operatively connected to the compressor piston and configured to rotatably drive the compressor piston; and

a third crankshaft operatively connected to the expander piston and configured to be rotatably driven by the expander piston;

wherein the first, second, and third crankshafts are operatively connected to each other for coordinated rotation.

2. The engine according to claim **1**, wherein the first, second, and third crankshafts are disposed alongside and parallel relative to each other.

3. The engine according to claim **1**, further comprising an intake port configured to transfer the compressed air from the compressor piston to each of the cooperating power pistons, and an exhaust port configured to transfer exhaust gases from each of the cooperating power pistons to the expander piston, the intake and exhaust ports are arranged such that the compressor piston is positioned on one side of the plurality of cooperating power pistons, and the expander piston is positioned on the opposite side of the plurality of cooperating power pistons.

4. The engine according to claim **1**, further comprising first, second, and third interconnected gears, wherein the first gear is connected to the first crankshaft, the second gear is connected to the second crankshaft, and the third gear is connected to the third crankshaft.

5. The engine according to claim **4**, wherein the first, second, and third gears are interconnected via at least one chain.

6. The engine according to claim **4**, wherein the first, second, and third gears are intermeshed.

7. The engine according to claim **6**, wherein the first gear has a handed helix, and the second and third gears have an oppositely handed helix as compared to the handed helix of the first gear.

8. The engine according to claim **1**, further comprising first, second, and third pulleys, wherein the first pulley is connected to the first crankshaft, the second pulley is connected to the second crankshaft, and the third pulley is connected to the third crankshaft, and the first, second and third pulleys are operatively connected via at least one belt.

9. The engine according to claim **1**, wherein the first, second, and third crankshafts are operatively connected for synchronous rotation.

10. The engine according to claim **1**, wherein the second and third crankshafts are configured as balance shafts for smoothing-out operation of the engine.

11. A vehicle comprising:

a body;

a plurality of wheels;

a split-cycle internal combustion engine including:

a cylinder block;

a plurality of cooperating power pistons and cylinders mounted in the cylinder block, the power pistons configured to be energized by forces of combustion;

a compressor piston and cylinder mounted in the cylinder block and configured to compress a volume of air and transfer the compressed air to the power pistons;

an expander piston and cylinder mounted in the cylinder block and configured to receive exhaust gases from the power pistons;

a first crankshaft operatively connected to and rotatably driven by the power pistons;

a second crankshaft operatively connected to the compressor piston and configured to rotatably drive the compressor piston;

a third crankshaft operatively connected to the expander piston and configured to be rotatably driven by the expander piston;

wherein the first, second, and third crankshafts are operatively connected to each other for coordinated rotation; and

a driveline connecting the split-cycle internal combustion engine to at least one of the plurality of wheels for powering the vehicle.

12. The vehicle according to claim **11**, wherein the first, second, and third crankshafts are disposed alongside and parallel relative to each other.

13. The vehicle according to claim **11**, further comprising an intake port configured to transfer the compressed air from the compressor piston to each of the cooperating power pistons, and an exhaust port configured to transfer exhaust gases from each of the cooperating power pistons to the expander piston, the intake and exhaust ports are arranged such that the compressor piston is positioned on one side of the plurality of cooperating power pistons, and the expander piston is positioned on the opposite side of the plurality of cooperating power pistons.

14. The vehicle according to claim **11**, further comprising first, second, and third interconnected gears, wherein the first gear is connected to the first crankshaft, the second gear is connected to the second crankshaft, and the third gear is connected to the third crankshaft.

15. The vehicle according to claim **14**, wherein the first, second, and third gears are interconnected via at least one chain.

16. The vehicle according to claim **14**, wherein the first, second, and third gears are intermeshed.

17. The vehicle according to claim **16**, wherein the first gear has a handed helix, and the second and third gears have an oppositely handed helix as compared to the handed helix of the first gear.

18. The vehicle according to claim **11**, further comprising first, second, and third pulleys, wherein the first pulley is connected to the first crankshaft, the second pulley is connected to the second crankshaft, and the third pulley is connected to the third crankshaft, and the first, second, and third pulleys are operatively connected via at least one belt.

19. The vehicle according to claim **11**, wherein the first, second, and third crankshafts are operatively connected for synchronous rotation.

20. The vehicle according to claim **11**, wherein the second and third crankshafts are configured as balance shafts for smoothing-out operation of the engine.

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